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CM-P00063958

MEASUREMENTS OF π^-p ELASTIC SCATTERING IN

THE COULOMB INTERFERENCE REGION AT HIGH ENERGIES

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ABSTRACT

The differential cross-section has been measured at 30, 50, 80, 100, 120 and 140 GeV/c for $0.002 < |t| < 0.04$ (GeV/c)². The results show that the π^-p real part goes from negative to positive values below 80 GeV/c. The slope parameter in the t-region measured is significantly higher than what has been found around $-t = 0.2$ (GeV/c)².

Geneva - 26 June 1978

(Submitted to Physics Letters B)

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In most fixed-target measurements of the differential cross-section for elastic scattering in the Coulomb interference region the forward scattered particle alone has been measured^{1,2)}. There are also experiments which have specialized in the measurement of the recoil only^{3,4)}. In the experiment reported on in this letter we measure both the proton recoil, using a specially developed ionization chamber spectrometer, and the forward scattered beam particle, using a multiwire proportional chamber (MWPC)-magnet spectrometer. One advantage of this method is the better resolution in four-momentum transfer squared t obtained with the recoil measurements in the Coulomb interference region [Δt of the order of $10^{-4} \text{ (GeV/c)}^2$] as compared with the forward particle measurement [Δt of the order of $5-10 \times 10^{-4} \text{ (GeV/c)}^2$]. Another advantage is the more efficient background rejection obtained from the simultaneous measurement of the recoil and the forward particles, as compared with experiments where measurements are made of only one of these particles. Our method furthermore provides absolute normalization of the measured cross-section.

A schematic layout of the experiment is given in Fig. 1 showing the ionization chamber (IKAR), the forward MWPC-magnet spectrometer, the particle identifiers and the trigger scintillators.

The ionization chamber contains pure hydrogen gas at a pressure of 1000 kPa. This gas serves both as target and as ionization medium. The chamber has six modular cells, each of which contains an anode plate and a cathode plate, 12 cm apart, mounted perpendicularly to the beam direction with an earthed wire grid 2 cm from the anode. The anode plate is divided in three concentric rings (A, B and C, see Fig. 1). The recoil kinetic energy and polar angle are derived from the height and the rise-time of the anode pulse, respectively. Kinetic energies in the region from 1 MeV to about 20 MeV, were measured in the experiment. Recoil protons of up to about 5 MeV are stopped inside the sensitive region of IKAR and for higher kinetic energies, only part of the energy is deposited in IKAR. The delay of the anode pulse with respect to the passage of the beam particle is a measure of the position of the recoil track within the chamber. A chamber containing only one modular cell, used in an earlier experiment, has been described elsewhere⁵⁾.

The forward spectrometer consisted of 30 MWPC planes with 1 mm wire spacing and a magnet with a bending angle of ~ 10 mrad. For each horizontal and vertical track coordinate, a minimum of two MWPC planes were used, except for the vertical coordinates downstream of the magnet, where only one plane per coordinate was used. The use of double planes provided good efficiency of the MWPCs and higher space resolution. To improve the resolution further for some runs a new mode⁶⁾ of operation was used in which the MWPC planes of PC1, PC2, and PC3 were turned with respect to the beam direction by a certain angle. This angle was such that there was equal probabilities of having one single wire and two adjacent wires giving signals. The useful areas of the chambers were $32 \times 32 \text{ mm}^2$ in PC1, PC2, and PC4, and $192 \times 192 \text{ mm}^2$ for PC3, PC5, PC6, and PC7. Another MWPC-magnet spectrometer (not shown in Fig. 1), placed in the incident beam, was used to measure the momentum of each incident particle.

A differential Čerenkov counter (CEDAR) was used to detect incident K's, and two threshold Čerenkov counters, both with the mass threshold set at $0.8 \text{ GeV}/c^2$, were used to separate p's from π 's. For the detection of muons two scintillation counters were placed downstream of the beam stopper (3.2 m of iron), and a lead-scintillator sandwich counter was used to identify electrons.

The rate of the incident secondary beam was about 6×10^5 particles per 600 msec effective spill. The trigger in the experiment was formed on three sequential levels. The first level was based on signals from a set of scintillators (counter S1 and anticounters A1 to A5 in Fig. 1). The second level trigger was produced within 250 nsec by a Special Digital Processor Unit⁷⁾ connected to PC1, PC2, and PC3, requiring the incident particle to have a scattering angle above a certain minimum value. The third level trigger was obtained from the recoil pulses in IKAR. The reduction in the trigger rate was about a factor of 100 for each of the second and third level triggers.

In parallel with the data acquisition of real event triggers, test pulses were generated by a test generator and sent to the electrodes of IKAR. These pulses were produced with a series of fixed amplitudes in a range, corresponding to measured

recoil energies, and with a series of fixed delays of the anode pulses, corresponding to the measured positions of the recoil track. Each test pulse was sent in coincidence with a real incident beam particle, and the detectors in the experiment were read out onto tape for each such test event.

The best estimate of the four-momentum transfer squared was obtained from the measured recoil kinetic energy in the low momentum transfer region $[0.002 < |t| < 0.01 \text{ (GeV/c)}^2]$, corresponding to recoils stopping in IKAR] and from the forward scattering angle at higher momentum transfers. The boundaries of the t range, $|t|_{\min} = 0.002 \text{ (GeV/c)}^2$, $|t|_{\max} = 0.04 \text{ (GeV/c)}^2$ $[0.02 \text{ (GeV/c)}^2 \text{ at } 30 \text{ GeV/c and } 0.03 \text{ (GeV/c)}^2 \text{ at } 140 \text{ GeV/c}]$ were defined by the requirement that there should be no t -dependence in the detection efficiency within the t range studied.

The standard error in the recoil kinetic energy in the low momentum transfer region was 60 keV. This error was determined from the pulse-height spectrum of the test signals. The corresponding error in four-momentum transfer squared t is $1 \times 10^{-4} \text{ (GeV/c)}^2$. The standard error in t , as determined from the forward scattering angle in the region $0.002 < |t| < 0.01 \text{ (GeV/c)}^2$ was $5\text{--}10 \times 10^{-4} \text{ (GeV/c)}^2$ at 120 GeV/c incident momentum, and $3\text{--}6 \times 10^{-4} \text{ (GeV/c)}^2$ at 30 GeV/c.

The recoil energy scale was calibrated using signals produced by 4.777 MeV alpha particles, which were emitted from radiative sources (^{234}U) deposited on the electrodes of IKAR. It was assumed that the collected ionization charge was proportional to the kinetic energy of the ionizing particle. The linearity and the stability of the amplifying, pulse-shaping and digitizing electronics were checked using the test event data. In this way the anode pulse-height response to recoil energy was controlled to a precision of ± 10 keV during the runs.

The $(p \cdot \theta)^2$ scale (p = incident momentum, θ = scattering angle) of the forward spectrometer was calibrated at one point $[(p \cdot \theta)^2 = 2 \times m_{\text{He}} \times 4.777 \times 10^{-3} \text{ (GeV/c)}^2]$, m_{He} = mass of ^4He nucleus] in special runs with the ionization chamber filled with helium instead of hydrogen. The precision in the calibration of this point was 0.4-0.6% in the p range 50-140 GeV/c.

A certain amount of the events acquired were eliminated because the measurement of the events had been disturbed by parasitic tracks or by inefficiencies in some of the detectors, because the incident track was too far from the central beam axis to allow full acceptance in the forward direction, or because the scattered beam particle was not a pion. In order to derive by what fraction the incident beam monitor count should be reduced to compensate for this loss of events it was evaluated what fraction of the test events was eliminated for the same reasons. As the criteria for acceptance of an event were the same for test events and for real events, these criteria could be made severe enough to allow a satisfactory suppression of "bad" events without perturbing the absolute normalization.

The effective target length was determined from the measured delay of the anode pulses. Electron drift velocity determinations were made in all six IKAR cells. The dispersion in the sample of the six measurements was of the order of 0.4%, from which was concluded an error of the same order in the determination of the total target length. The stability and linearity of the electronics used to measure the drift time were monitored throughout the data taking with the aid of the test events. The pressure and temperature of the gas in the ionization chamber were measured with a precision allowing a determination of the gas density to $\pm 0.2\%$

The following kinematical and geometrical constraints were used to select the elastic events:

- i) The momentum of the scattered particle should be equal to the momentum of the incident particle.
- ii) The four-momentum transfer squared calculated from the recoil ($-t = 2 m_r T_r$) and that calculated from the forward particle [$-t \approx (p \cdot \theta)^2$] should be equal.
- iii) The recoil kinetic energy and polar angle should follow the correlation for elastic events.
- iv) The partial energy losses of the recoil particle measured by the anode rings A and B should agree with the relation for energy loss of a proton in hydrogen.

v) The tracks of the incident and of the outgoing forward particle should intersect at a point whose longitudinal coordinate was given by the drift time measurement in IKAR.

The following parametrization was fitted to the measured differential cross-sections

$$\frac{d\sigma}{dt} = \frac{4\pi\alpha^2}{\beta^2 |t|^2} G_\pi^2 G_p^2 + (1 + \rho)^2 \frac{\sigma_{\text{tot}}^2}{16\pi} e^{-b|t|} - Q \frac{\sigma_{\text{tot}}^\alpha}{\beta |t|} (Q \sin \delta + \rho \cos \delta) e^{-\frac{1}{2}b|t|} G_\pi G_p$$

where α is the fine structure constant ($1/137$), β is the velocity of the incident particle, σ_{tot} is the total hadronic cross-section, ρ is the ratio of the real to imaginary part, b is the logarithmic slope of the hadronic cross-section, $G_\pi = (1 - t/0.59)^{-1}$ and $G_p = (1 - t/0.71)^{-2}$ are the electromagnetic form factors of the pion and the proton⁸⁾, respectively, $\delta = -[\ln(|t|/0.07) + 0.577] \times \alpha/\beta$ is the Bethe phase⁹⁾ and Q is the charge of the incident particle.

Both the real part ρ and the slope b were used as free parameters in the fits at all energies except at 30 GeV where the t -range was too small to make a good determination of the value of b . Consequently only ρ was left as free parameter at this energy and the value for b used was the mean of the b values obtained in the fits at the other energies. The measured absolute normalization was used to constrain the $d\sigma/dt$ scale with a standard error of 1% (1.5% at 140 GeV/c) in the fit and the results of the total cross-section measurements made by Carroll et al.¹⁰⁾ were used to constrain the value of σ_{tot} . The results of the fits are given in Table 1.

Our results on ρ rely on the precision of the absolute normalization in the experiment and on the values used for σ_{tot} . The shift in the value of ρ is +0.01 for a -1% shift in the normalization or a -0.2 mb shift in σ_{tot} . The errors used in the fit for σ_{tot} are the statistical errors as quoted in Ref. 10. The uncertainty of 0.4% in the σ_{tot} scale, as quoted in Ref. 10, corresponds to a scale uncertainty of 0.005 in our ρ values. The correlation between ρ and b in the fit is such that a shift of $+1 \text{ (GeV/c)}^{-2}$ in b corresponds to a shift $\Delta\rho = +0.003$ in ρ .

The resulting ρ values are plotted with their errors in Fig. 2. In this figure are also shown data from other experiments^{1,2,11)} and predictions from dispersion relation calculations^{12,13)}. Our data show that the π^-p real part has gone to positive values already below 80 GeV/c. The dispersion relation predictions are in good agreement with the data. In particular, we find no strong deviation from dispersion relation calculations at 30 GeV/c, in contrast to results from some earlier experiments^{1,11)}.

Our results on the slope parameter are given in Table 1. They show that the slope in our t region $[-t < 0.04 (\text{GeV}/c)^2]$ is significantly bigger than the slope at $-t = 0.2 (\text{GeV}/c)^2$ measured by Ayres et al.¹⁴⁾ to be $8.45 \pm 0.06 (\text{GeV}/c)^{-2}$ at 50 GeV/c and $8.28 \pm 0.07 (\text{GeV}/c)^{-2}$ at 140 GeV/c. A tendency for the slope to increase at small t has also been seen in the experiment of Ankenbrandt et al.²⁾. This change in the π^-p slope parameter could be similar in nature to the change found in pp elastic scattering at small t . The data show no significant s -dependence for the slope.

This experiment was carried out at the CERN SPS. Invaluable assistance from the CERN Experimental Area group and from the technical staff of our home laboratories is gratefully acknowledged.

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- 15) The data point $\rho = -0.037 \pm 0.017$ at 40 GeV/c in Fig. 2 has been obtained by G.A. Korolev et al. in a similar experiment at the Serpukhov accelerator, also using the ionization chamber. An account of this experiment has been submitted to Physics Letters.

Table 1

Values of ρ and b resulting from the fit

p_0 [GeV/c]	t region [(GeV/c) ²]	No. of events	$\sigma_{\text{tot}} \pm \Delta\sigma_{\text{tot}}$ (From Ref. 10) [mb]	$\rho \pm \Delta\rho$ Fitted	$b \pm \Delta b$ Fitted [(GeV/c) ⁻²]
30	0.002-0.02	20,000	24.61 ± 0.06	-0.04 ± 0.02	$11.1^{*)}$
50	0.002-0.04	78,000	24.06 ± 0.06	-0.003 ± 0.013	10.6 ± 0.3
80	0.002-0.04	94,000	23.99 ± 0.06	$+0.017 \pm 0.013$	11.2 ± 0.3
100	0.002-0.04	98,000	24.00 ± 0.06	$+0.023 \pm 0.013$	11.3 ± 0.3
120	0.002-0.04	68,000	24.06 ± 0.06	$+0.052 \pm 0.013$	11.3 ± 0.3
140	0.002-0.03	19,000	24.09 ± 0.04	$+0.03 \pm 0.02$	10.9 ± 0.8

*) Fixed value used at 30 GeV/c.

Figure captions

- Fig. 1 : Experimental layout showing the ionization chamber (IKAR), the forward spectrometer (PC1-PC7 and the magnet), the particle identifiers (CEDAR, Č1, Č2, e counter, μ counter), and the trigger scintillators (S1 and A1, A2, A3, A4, A5). Not shown is the MWPC-magnet spectrometer, upstream of the experiment, used to measure the momentum of the incident beam particles.
- Fig. 2 : Plot showing data available at present on the $\pi^- p$ real part above 10 GeV/c. The curves are from the calculations of Hhler et al.¹²⁾ and Engelmann et al.¹³⁾. In the calculations of Hhler et al., the total cross-section at high energies was assumed to be proportional to $\log^2 s$ for the full line curves and to $\log s$ for the dotted curve.

Fig. 1

S and A = scintillation counters
 PC = multiwire proportional chamber, 1 mm pitch
 Nos. 1, 2, and 4 are of dimensions $32 \times 32 \text{ mm}^2$
 Nos. 3, 5, 6, and 7 are of dimensions $192 \times 192 \text{ mm}^2$

Fig. 2